LIDAR-Generated Digital Elevation Models for Hazard Detection

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Feb. 3 2019

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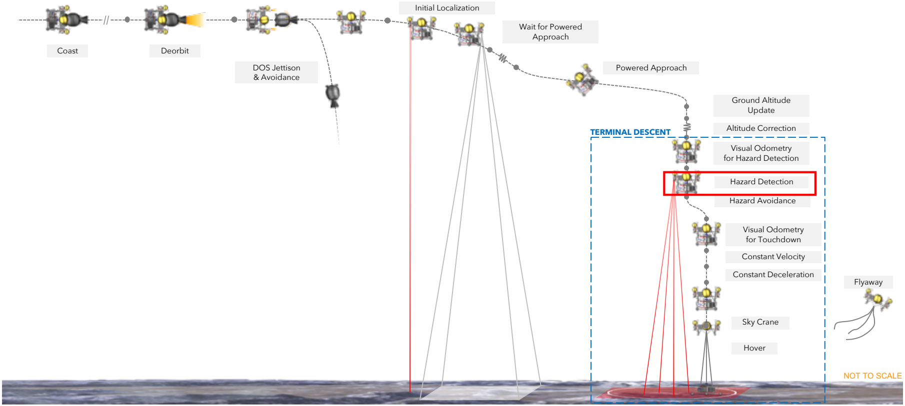
Overview

Key Features

- Modular geometric LIDAR models
- Integration with a dynamics simulator to model LIDAR measurements on moving platforms
- Modeling of measurement noises and state knowledge errors in DEM construction
- Develop tools to evaluate the LIDAR-generated DEM against the Europa Lander Mission Concept requirements

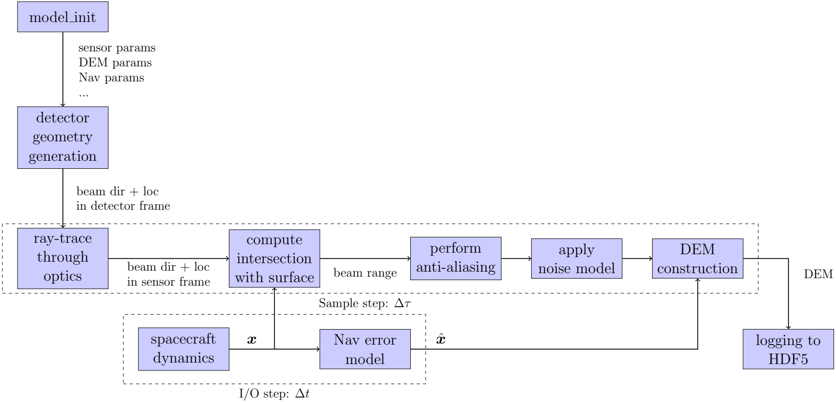
Deorbit Descent Landing Phases



- The Hazard Detection phase relies on a LIDAR-generated DEM

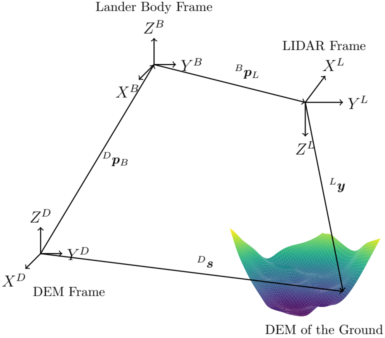
A. K. Zimmer, E. D. Skulsky, A. M. San Martin, G. Singh, N. Trawny, T. P. Kulkarni, and M. E. Greco, “Landing on Europa: Key Challenges and Architecture Concept,” 29th AAS/AIAA Space Flight Mechanics Meeting, Ka’anapali, HI, January 13-17, 2019.

LIDAR Model



- Developed as a software module for the DSENDS simulation architecture
- The LIDAR model consists of several individual modules. Each module can be replaced or adjusted to simulate a particular LIDAR configuration

Coordinate System



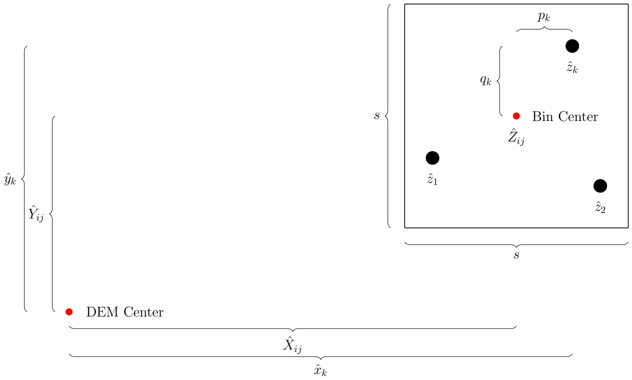
- Use ray-tracing and ray interception techniques to determine the true range from LIDAR to terrain
- Use navigation state knowledge to transform $^L\boldsymbol{y}$ to $^D\boldsymbol{s}$ for DEM construction

$$\begin{bmatrix} ^D\boldsymbol{s} \\ 1 \end{bmatrix} = {}^D_L H \begin{bmatrix} ^L\boldsymbol{y} \\ 1 \end{bmatrix}, \quad {}^D\boldsymbol{s} = \begin{bmatrix} x & y & z \end{bmatrix}^T$$

Parameters of the LIDAR Model

- Detector geometry and scanning mechanism
  - Number of pixels
  - Field-of-view
  - Scanning pattern
- Measurement noise model
  - Range noise
  - Range bias
  - Pixel dropout
  - Dead pixel
- Navigation state knowledge error model
  - Deterministic error, ${}^{D}\tilde{\boldsymbol{p}} = \boldsymbol{a}_p + \boldsymbol{a}_v(t - t_0)$
  - Position bias, velocity error, angular bias, and angular rate error
  - Add errors in lander body frame and DEM frame transformation, ${}^{D}_{L}H$

DEM Construction



- Based on the weighted average of all measurements within a bin

$$\hat{Z}_{ij} = \sum_{k=1}^{N} w_k \hat{z}_k, \quad w_k = \frac{\breve{w}_k}{\sum_{k=1}^{N} \breve{w}_k}, \quad \breve{w}_k = (1 - q_k)(1 - p_k).$$

DEM Requirements

- Coverage
  - The number of invalid pixels cannot exceed 1% of the mapped region.
  - Following the 8-connected rule, the number of connected invalid pixels cannot exceed 10 pixels.
  - The maximum distance from an invalid pixel to the nearest valid pixel cannot exceed 1 pixel.
- Accuracy
  - The elevation error of all valid pixels over the lander footprint shall not exceed 5 cm (95%ile) over the entire mapped region.
  - The horizontal error of all valid pixels over the lander footprint shall not exceed 5 cm (95%ile) over the entire mapped region.
  - The mean horizontal error over a lander footprint shall not exceed 1 m for 95% of the entire map.

DEM Evaluation Metrics

- Coordinate errors

$$e_{X,ij} = X_{ij} - \hat{X}_{ij}, \quad e_{Y,ij} = Y_{ij} - \hat{Y}_{ij}, \quad e_{Z,ij} = Z_{ij} - \hat{Z}_{ij}$$

- Absolute error metrics

$$\breve{e}_{X,ij} = mean(e_{X,lk}), \quad \breve{e}_{Y,ij} = mean(e_{Y,lk}), \quad \breve{e}_{Z,ij} = mean(e_{Z,lk})$$

- The l and k indices are evaluated over the lander footprint
- Relative error metrics

$$\tilde{e}_{X,ij} = Q_q(|e_{X,lk} - \breve{e}_{X,ij}|), \quad \tilde{e}_{Y,ij} = Q_q(|e_{Y,lk} - \breve{e}_{Y,ij}|),$$

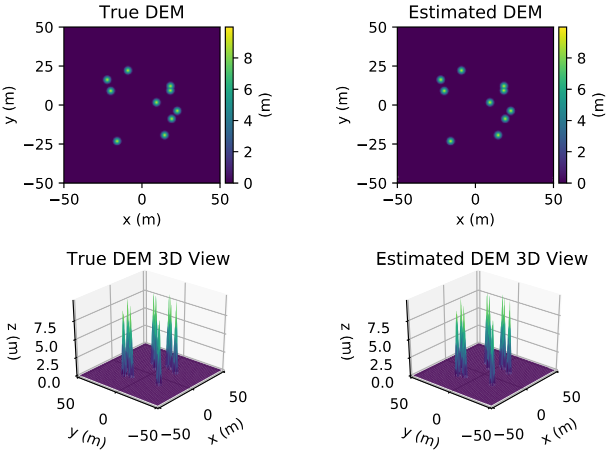
$$\tilde{e}_{Z,ij} = Q_q(|e_{Z,lk} - \breve{e}_{Z,ij}|)$$

Simulation Setup

- Vertical descent in Europa gravity from 500 m altitude with constant vertical velocity of -23 m/s
- Scanning mechanism is a fast steering mirror following a line-search pattern
- LIDAR scanning time is 2 seconds at 20 kHz rate
- DEM resolution is 5 cm
- 2 Examples
  - Artificial DEM with primitives
    - No measurement or navigation state knowledge errors
  - Europa DEM
    - 5 cm range noise (3σ)
    - Velocity bias errors, $[0.3, 0.3, 0.7]$ m/s in X, Y, and Z directions

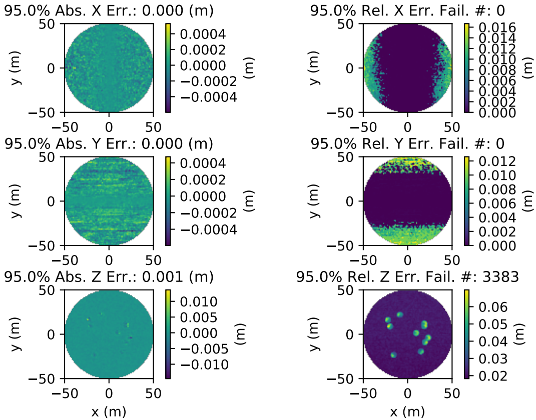
Line-Search Scanning Pattern

Example 1: DEM



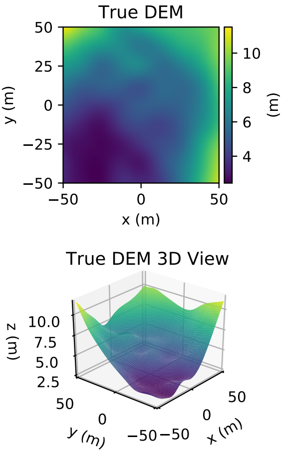
- True terrain is a plane with 10 circular cones (10 m height and 3 m radius)

Example 1: Evaluation



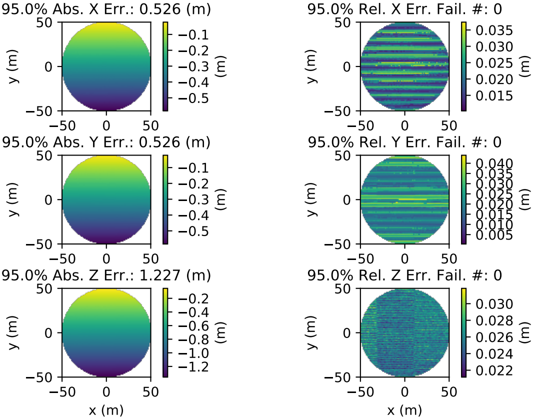
- Horizontal errors are due to measurement sorting
- Elevation error is due to large elevation change over a small area (quantization error)

Example 2: DEM



- True DEM is an interpolation of a 12.5 m resolution Europa DEM

Example 2: Evaluation



- The navigation error is captured by the absolute error metrics
- The range measurement noise is captured by the relative elevation error metric (Z-direction)

Future Work

- Use this simulation to perform trade studies
  - Detector geometry
  - LIDAR scanning mechanisms and patterns
  - Error model parameters
  - DEM construction methods
  - Ground terrain
- Include additional LIDAR components
- Improve model fidelity
- Implement the covariance propagation equation to generate a DEM uncertainty map

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